The Cavendish Gas Field, Block 43/19, UK Southern North Sea

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Abstract: The Cavendish Field is located in UKCS Block 43/19a on the Northern margin of the Outer Silverpit Basin of the Southern North Sea, 87 miles (140 km) north-east of the Lincolnshire coast in a water depth of 62 ft (18.9 m). The Cavendish Field is a gas field in the Upper Carboniferous Namurian C (Millstone Grit Formation) and Westphalian A (Caister Coal Formation). It was discovered in 1989 by Britoil operated well 43/19-1. Production started in 2007 and ceased in 2018. Gas-initially-in-place was 184 Bscf and at end of field life 98 Bscf had been produced. The field was developed by three wells drilled through the normally unmanned platform into fluvio-deltaic sandstone intervals that had sufficiently good reservoir quality to be effective reservoirs. The majority of the formation within closure comprises mudstones, siltstones and low permeability, non-reservoir quality feldspathic sandstones. The quality of the reservoir is variable and is controlled by grainsize, feldspar content and diagenesis. The field is a structural trap, sealed by a combination of intra-Carboniferous mudstones and a thick sequence of Permian mudstones and evaporites.

Keywords: Cavendish, tight gas, Carboniferous, fluviodeltaic sediments

The Cavendish Field, currently operated by INEOS UK SNS Limited, is located within UKCS Block 43/19a (Figure 1). The block is located on the Eastern margin of the Outer Silverpit Basin of the Southern North Sea (SNS), 87 miles (140 km) north-east of the Lincolnshire coast in a water depth of 62 ft (18.9 m). The field is approximately 7.5 miles (12 km) long and covers an area of 13.7 sq miles (35.5 km^2).

History of exploration and appraisal

Block 43/19 was awarded to the Britoil/Amoco Consortium (Britoil 50% as operator, Amoco 50%) as part of the 10th Round of Licencing in 1987, with the commitment to drill two exploratory wells to test for gas expected to be within Upper Carboniferous sandstones, to penetrate at least 300 ft (91.4 m) of the Namurian section, and to acquire 155 miles (250 km) of 2D seismic within the block.

The first well on the block, 43/19-1 was drilled in 1989 by Britoil over the centre of the prospect and slightly down dip of the structural crest. It found Carboniferous strata subcropping beneath the Base Permian Unconformity (BPU) at 11450 ft (3490 m) TVDSS (Table 1). The well successfully tested gas from two intervals in late Carboniferous Westphalian A and Namurian B-C sandstones. Cores were taken in three separate intervals in the Namurian section. Drill stem test (DST) 1 was conducted over two quartzitic sandstones 12 and 20 ft (3.7 and 6 m) thick in the Namurian section and flowed combined at 14.6 MMscf/d of gas and 230 bbl/d of condensate. DST 2a was conducted on an 18 ft (5.5 m) thick, quartzitic Westphalian A sandstone (Figure 2) immediately below the BPU and flowed gas at 32.6 MMscf/d and condensate at 240 bbl/d. The gas-down-to level in this well was 11906 ft (3629 m) TVDSS proving a minimum gas column height of 456 ft (139 m).

Appraisal well 43/19-2A was drilled in 1990 by Amoco and located 1.4 miles (2.2 km) west of the discovery well. This well encountered a thicker section of Westphalian A below the BPU with two different gas-bearing sandstones stratigraphically younger than those seen in 43/19-1. The quartzitic sandstone (thought to be equivalent to the Crawshaw Sandstone onshore UK) tested in 43/19-1 was water bearing. The well also penetrated an 1800 ft (549 m) Namurian interval ranging in age from Marsdenian to Pendleian. Numerous sandstone intervals were found but most were tight. Out of 90 repeat formation tests (RFTs) attempted, only six were considered valid tests. Three DSTs were conducted on Westphalian sandstones. DSTs 1 and 2 failed to flow on test due to low permeability formation. DST 3 was conducted over a thin Westphalian A quartzitic sandstone, and flowed gas at 17 MMscf/d and 91 bbl/d of condensate. RFT pressure measurements made in the water leg enable a free water level (FWL) estimate of 11960 ft TVDSS. This extended the proven gas column height to 510 ft (155 m).

Further delineation of the field occurred in 1996 when Amoco drilled well 43/19a-4Z from the same top-hole location as 43/19-2A, to a bottom-hole location 1.4 miles (2.3 km) further west. This test of the western flank proved a more extensive Westphalian A section below the BPU however, the permeable Westphalian sandstone intervals were beneath the FWL. In this well, the longest continuously cored section of the Carboniferous yet made in the UK SNS was acquired, from 14779 ft MDBRT (4504.6 m) in the Westphalian A to 16858 ft MDBRT (5138.3 m) in the Kinderscoutian, totalling 2079 ft (634 m) of continuous coring.

The appraisal programme had proven a gas-bearing structure though the gas composition had inert gas (CO_2 and N_2 combined) >7%. This gas quality alone would be below specification for entry to the National Transmission System (NTS). Commercial production rates had been proven from three separate sandstone intervals but there were a larger number of sandstones that were considered to have permeabilities that were too low to sustain economic gas production. Amoco's interest was acquired by BP in1998 through the merger of BP and Amoco and in 2000 the licence was sold to Highland Energy, which was then acquired by RWE-Dea in 2002.

Development

A reduction in the calorific value entry specification in the NTS and the availability of low CO_2 blend gas from Saturn and Topaz fields to add to gas from fields produced via the Lincolnshire Offshore Gas Gathering System (LOGGS) and Caister Murdoch System (CMS) pipelines allowed Cavendish gas to be considered for production through the Theddlethorpe gas terminal. This combined with rising gas prices in the first decade of the 21st century led to renewed interest in the field by the new operator RWE-Dea. The field development plan (FDP) was for a three well development from a six slot, normally unattended, remotely operated, minimum facilities platform tied-back with a 28 mile (45 km) 10 inch pipeline to the Murdoch platform to the south east. From Murdoch gas was to be exported through the CMS trunk pipeline to Theddlethorpe in Lincolnshire. The FDP was approved by the government in 2005 with the partnership group comprising RWE Dea UK 50% and operator, Dana 25% and Gaz de France 25%.

Three development wells were drilled through the platform slots in 2006 and 2007 (Table 1). Well 43/19a-C1 was located in the centre of the field, twinning exploration well 43/19-1. The well was completed in three intervals, two Westphalian A sandstones and a deeper Marsdenian age sandstone. Well 43/19a-C2 was drilled to the west to develop the thicker but marginal quality Westphalian sandstones seen in 43/19a-2A. The 43/19a-C2 well did not encounter the same thin high permeability quartzitic sandstone interval tested on 43/19-2A and was side-tracked down-dip as 43/19a-C2Z. However the side-track also proved unsuccessful. The well was side-tracked a second time in 2010 as 43/19a-C2Y and eventually put on production. Well 43/19a-C3 was drilled to the south of the platform to ensure there was a second producer from the high quality Crawshaw Sandstone equivalent and to mitigate the risk of any potential fault compartmentalization.

Regional Context

Basin evolution

The Southern North Sea Basin experienced a complicated geological history, involving multiple episodes of uplift and subsidence. During Carboniferous times the basin was bounded in the south by the London Brabant Massif and in the north by the Mid North Sea High/Ringkøbing-Fyn High (Cameron et al., 1993), with over 19685 ft (6000 m) of sediments deposited in parts of the basin (Besly, 2018). The Variscan Orogeny resulted in faulting and folding of the Carboniferous rocks and subsequent erosion of much of the Upper Carboniferous strata. During Permian times, renewed subsidence of the Variscan foreland resulted in deposition of a thick sequence of mainly clastic and evaporite strata deposited initially in continental and subsequently restricted marine environments, which were for short periods connected to the ocean through constricted seaways, resulting in hypersaline conditions (Cameron et al., 1993; Ziegler, 1990). Subsidence, with additional extensional faulting, continued into the Triassic, accompanied by regional regression. Deposition in the Southern North Sea Basin was dominated by fine grained clastics and evaporites with coarse grained clastics in the Early Triassic, formed within fluvial, sabkha, lacustrine and shallow marine environments (Fisher and Mudge, 1998, Johnson et al., 1994). End Triassic to Early Jurassic crustal extension caused rapid subsidence, and a major transgression in the Jurassic times marked the onset of deposition of predominantly shallow marine muds and limestones (Lott and Knox, 1994). This period of subsidence was interrupted by thermal doming in the Central North Sea, which caused uplift and erosion of much of the Jurassic sequence in the region. Crustal extension continued after the uplift until mid-Cretaceous times providing accommodation space for a thick, predominantly marine sequence. An episode of uplift at the end of the Cretaceous caused basin inversion in many fault-bounded basins such that Paleogene marine deposits unconformably overlie the Cretaceous Chalk deposits. Miocene tectonic uplift linked to the Alpine Orogeny removed part of the Palaeogene sequence, capped by a major Pliocene deltaic system (Cameron et al., 1992, Cameron et al., 1993).

Stratigraphy

At the time of FDP submission (2005) the three key productive sand intervals were identified as Reservoir Layers '1', '2' and '3' and dated as mid Marsdenian (Namurian B-C) to Langsettian (Westphalian A). These layers are part of the Millstone Grit Fm. (Namurian) and Caister Coal Fm. (Westphalian) and using onshore stratigraphic terminology (e.g. BGS, 2019) were later named as the Guiseley Grit (layer 1), Crawshaw Sandstone (layer 2), and Loxley and Alton Sandstones (layer 3; Figure 2). The Loxley Sandstone is an informal abbreviation of the formal Loxley Edge Sandstone and the Alton Sandstone is an informal field name for sandstone which occurs just beneath the *G. listeri* marine band. These zones were identified through a multi-well biostratigraphy study that included wells outside the development area. Using palynostratigraphic methods a number of likely marine band equivalent mudstones were identified (Figure 2) that are recognised over areas of the offshore Carboniferous play and are correlatable to onshore stratigraphic events (Waters et al., 2009). The palynostratigraphy is constrained by the cored section from well 43/19a-4Z, from which macropalaeontological data are available. Well correlation based on palynostratigraphy is improved by palaeovegetational analysis, providing a high-resolution framework. The study allows a high level of confidence to be applied to the well correlation (Figure 3a and 3b) and is fully consistent with the seismic interpretation and mapping.

The oldest producing horizon on the Cavendish field is the mid- Marsdenian age Guiseley Grit equivalent and occurs immediately below the *Bilinguites superbilinguis* marine band (Figure 2). The interval is subdivided into an upper and lower sandstone unit separated by a thin mudstone. The sandstones were probably deposited by a major distributary channel within a shallow water prograding delta front.

The overlying Yeadonian interval comprises mudstones with sporadic sandstone intervals. These sandstones are of non-reservoir quality and probably originate as minor distributary channels or over bank crevasse splay type deposits.

The base of the Westphalian interval is marked by the marine band *Gastrioceras subcrenatum*. Immediately above this marine band is the Crawshaw Sandstone (Figure 2). These quartzitic sandstones may have originated as the result of a base level change and been deposited as incised valley fill over a wide area. The origin of quarzitic sandstones in Upper Carboniferous strata has been widely discussed. O'Mara et al. (1999 and 2003) suggest that quarzitic sandstones encountered in the nearby Trent field are a product of tidal reworking. An alternative explanation given by Bristow (1988) for the origin of time equivalent, quarzitic Rough Rock sandstones in more distal parts of the basin is the proximal to distal degradation of feldspars resulting in quartz enrichment in distal parts, and to sediment supply to the basin by two different river systems. An unpublished proprietary report for the operator proposed the quarzitic sandstones to have a diagenetic origin due to feldspar dissolution and a lesser amount of kaolinite precipitation in intervals near marine bands.

In the early Westphalian interval above the Crawshaw Sandstone, the Loxley Sandstone and Alton Sandstone are separated by the *G. listeri* marine band. These sandstones have average thicknesses of 58 ft (17.8 m) and 77 ft (23.4 m) respectively and are characterised by low porosity, low permeability feldspathic sandstones.

Source

Westphalian and Namurian coals and mudstones (Westoe Coal and Caister Coal Formation, Millstone Grit Formation) are considered to be a source rock for many of the fields with Carboniferous reservoirs in the region (Cameron and Ziegler, 1997; Cornford, 1998). The operator's unpublished proprietary reports propose gas charging probably started in Cretaceous times. This is in agreement with data elsewhere in the SNS area (Middle Jurassic reported by Robinson et al., 1993, Jurassic or Cretaceous by Besly, 2018). Thermal maturity data show that the Upper Carboniferous deposits in the Cavendish Field are currently in the oil generation window, with vitrinite reflectance values from 0.65-0.78% Ro.

Database

Well data included exploration and appraisal wells over the field and offset wells that have significant penetration of the Carboniferous interval. Multi-well studies were completed prior to development that made use of the wireline logs, core and PVT data.

A 529 sq. miles (1370 km^2) 3D seismic survey was acquired by Geco-Prakla in 1993/94 over the Cavendish field. Initially the data were processed with a Dip Move-Out (DMO) stack and post-stack 3D phase-shift migration to produce a conventional time migrated dataset. The dataset was subsequently re-imaged in the post-stack depth domain for Amoco in 1995 resulting in a post-stack depth migrated (PostSDM) dataset.

This PostSDM volume provides clearer definition of faults within the Carboniferous section, partly at the expense of true amplitude relationships. Both datasets suffer contamination from long-period multiples. During 2004 the dataset was reprocessed in the time domain (pre stack time migration) in an attempt to reduce the number of multiples. This exercise was only partially successful as the resultant dataset still suffers from some long period multiples.

Seismic interpretation has used both data sets to provide a high level of confidence in the mapping. Below the Base Permian Unconformity two intra-Carboniferous horizons were picked and gridded. The deepest horizon is a near equivalent to the Guiseley Grit (Figure 2). The Crawshaw Sandstone is truncated below the Base Permian Unconformity on the crest of the structure. Depth conversion and a combination of error correction and isochore maps were used to produce a set of final top reservoir depth maps.

Trap

The Cavendish structure resulted from multiple deformation phases since late Carboniferous through to early Tertiary times. During the Late Carboniferous, northwest-southeast extension occurred creating a series of normal and listric style faults with northeast-southwest trends. Syn-sedimentary faulting produced a series of half-grabens which flank the main hanging-wall anticline. At intra-Carboniferous level, the Cavendish structure is a west northwest-east southeast orientated anticline. The axis plunges both east and west and is truncated to the east by a west southwest-east northeast trending fault. To the north the structure is bounded by a major west northwest-east southeast trending reverse fault and the flank to the south is steeply dipping (Figure 4). At the crest of the anticline the Crawshaw Sandstone is partially eroded by the Base Permian Unconformity (BPU) whilst a thick succession of Westphalian A interval is preserved on the flanks of the structure (Figure 4). The Base Permian Unconformity is characterised as a gently undulating surface with dip to the south and no expression of the underlying structure other than the reverse fault.

Early interpretation of the gas-water contacts (GWCs) based on log and pressure data identified a high and low depth range with a most likely contact at 11960 ft (3645 m) SS. This GWC was applied across the structure at the field development stage. Post development further analysis of well data provided the opportunity to review the GWCs of the various reservoir intervals and sealing mechanisms.

The regional seal is formed by the Permian, Silverpit Fm. siltstones and mudstones, which are effective over a wide area of the Carboniferous play in the SNS. In the absence of a common BPU closure each reservoir interval has a unique sealing mechanism and consequently have different GWCs. Gas compositional variations found during well testing (Table 2) demonstrate discreet reservoir intervals not in vertical communication and production subsequently demonstrated that they are not in pressure communication.

The interpreted GWCs are summarised;

A quartzitic interval in the Westphalian A (Loxley Sandstone): 11910 ft (3630 m) SS

The Crawshaw Sandstone equivalent: 12000 ft (3658 m) SS

Productive sandstone within the Marsdenian (Guiseley): 11950 ft (3642 m) SS

The Loxley-Alton Sandstones are proven on the western flank of the structure where a thick succession of Westphalian A is preserved below the BPU. The trapping mechanism requires a combination seal and this is provided by the Silverpit Formation where the reservoir units are truncated at the BPU and dip closure from a thick succession of shale in the Westphalian A above the reservoir interval where the structure plunges to the west. The Westphalian A shale interval is proven in well 43/19a-4z located down-dip to the west. Closure is mapped down to a spill point at 12087 ft (3684 m) SS which is approximately 170 ft deeper than the GWC in the quartzitic sand. It is likely that the spill point is either controlled by a shallower more effective shale interval in the Westphalian A or there is communication across the main boundary fault to the north with an unidentified sand interval. As the Loxley-Alton reservoir does not share a common GWC with the stratigraphically older but structurally higher Crawshaw Sandstone it may be assumed that an effective seat-seal or barrier is present between the two reservoir intervals.

The Crawshaw Sandstone has a combination seal of the Silverpit Formation where it is truncated at the crest of the structure by the BPU and the shale interval immediately above the reservoir in the Westphalian A and below the Loxley - Alton reservoir units. The GWC is the deepest of the three reservoir intervals at 12000 ft (3658 m) SS. A significantly deeper closure with a spill point at 12530 ft (3820 m) SS is located on the plunging axis to the west. A difference between structural closure and GWC of more than 500 ft (152 m) would suggest that the reservoir is in communication with a permeable sand juxtaposed across the reverse fault that potentially has a shallower spill point.

The Guiseley sandstone reservoir GWC proved more problematic to determine however, even with a depth range of potential GWC it is shallower (most likely case) at 11950 ft (3642 m) SS than the Crawshaw Sandstone although the reservoir interval is structurally deeper. The top Guiseley sandstone depth structure has similar form to the Crawshaw Sandstone although the crestal area of the structure is smaller and has an elevation that is deeper than the BPU. The intra-Carboniferous seal is most probably associated with shale intervals that are present above the marine bands (*B. superbilinguis* and *G.*

cancellatum) that occur between the Guiseley and Crawshaw Sandstones. Closure of the structure is greater than the observed GWC and it is assumed that cross-fault seal is the controlling factor of the observed gas column height.

Reservoir and petrophysics

The reservoir rock comprises Namurian to Westphalian A fluvial sandstones deposited by a southward-prograding fluviodeltaic system infilling a deep basin, which originally formed in Dinantian times. The whole Upper Carboniferous sequence consists of multiple cycles of coarsening upwards deposits with marine mudstones (marine bands) at their base and fluvial deposits at the top. The multi-storey fluvial channel sandstones are up to 26 m (85 ft; Kinderscoutian age, well 43-19a-4Z) in thickness, with net:gross ratios of 0.17-0.22. In terms of reservoir continuity, Collinson et al. (1993) suggested that the thinner channels (<33 ft; 10 m) have widths of 328 ft (100 m) or less, whilst channel sandbodies which are about 82 ft (25 m) thick are <6.2 mile (10 km) wide.

Facies

The Upper Carboniferous sequence penetrated in the three appraisal wells drilled in the Cavendish Field was extensively cored. Twenty five cores were obtained, eleven of which were described in detail, including grain size, sorting, sedimentary structures, sand/detrital clay content, bioturbation index, cements, lithofacies and facies associations. A number of facies associations have been identified, of which multi-storey fluvial channels and distributary fluvial channels comprise the reservoir. Non-reservoir facies associations include delta plain, shoreface, interdistributary bay, proximal delta front, distal delta front, prodelta and offshore muds.

Fluvial channels, which form the reservoir, are represented by light grey, moderately well sorted, predominately upper fine grained, 'clean' sandstones, interbedded with intervals of mid fine to upper very coarse grained sandstones, and local conglomerate beds which are up to 0.8 ft (25 cm) thick. Conglomerates are generally matrix supported and composed of rigid clasts and mudclasts of up to cobble grade. Sandstones are stacked in metre-scale intervals (up to 59 ft; 18 m) and locally contain mudclasts and rigid grains of up to pebble grade, and scattered fine carbonaceous debris. Crevasse splay deposits are represented by planar laminated sandy siltstone beds up to 0.4 ft (12 cm) thick, interbedded with the fluvial sandstones. Sandstone bodies are predominantly cross-stratified, with some intervals planar laminated, structureless or ripple cross laminated. Stacked sandstone bodies commonly display sharp tops. Sandstones are predominantly quartz cemented, with local dolomite cements.

Depositional model

On a large scale, the Namurian strata record filling of relic Dinantian basin topography, which consisted of a series of highs and graben (Figure 5), formed as a result of the convergence of Gondwana with Laurussia, the following rifting phase, and a subsequent phase of thermal subsidence (Waters and Davies, 2006). Large fluviodeltaic systems, mainly fed from the north, progressed southwards filling the accommodation space within the basin (Collinson et al., 1993; 2005). The overall Namurian sequence in a broad sense begins with marine mudstones, followed by deep-water delta-front turbidites, shallow-water sheet-like delta facies and large fluvial channels developed on top, following delta progradation. The huge fluvial system that developed during the Namurian times has likely drained continental-scale areas, with the Pennine river- delta system possibly comparable in size to modern Amazon (Leeder, 1988). The exposed granite/gneiss Caledonian hinterland was the main source of the sediment transported by extensive river systems. Paleocurrent analysis in well 43/19-1 shows that the channels in this locality flowed to the north northwest and northwest during the Namurian C and to the southeast during the Namurian B. This north northwest/northwest trend, contrasting with the larger regional observations, might be explained by a local structural control diverting the flow, as is found in some onshore areas in the UK (e.g. Bristow, 1998). As an effect of glacio-eustatic cyclicity (Davies et al., 1999), multiple marine transgressions occurred during the Namurian times resulting in stacking of numerous coarsening-upwards successions of genetically-related facies.

Reservoir quality

Reservoir quality in the sandstones varies from very low (0.01 mD, analysis threshold) to excellent (744 mD in 43/19a-4Z). Porosity (0.4-19.1%) appears to be partially controlled by depositional environment, whilst permeability is largely controlled by diagenetic processes.

The Guiseley Grit interval has an average thickness of 47 ft (14.2 m) and is subdivided into an upper and lower sandstone unit (informally called Guiseley Main) separated by a thin mudstone. The sandstones vary significantly in reservoir character with the upper sandstone having low porosity in the range of 2 to 7% and low permeability of less than 1 mD. The Guiseley Main sandstones generally have better reservoir characteristics with porosity in the range of 7 to 10% and permeability in the order of 25 to 400 mD. The Crawshaw Sandstone has an average thickness over the field of 25 ft (7.6 m) and has an average porosity 9.5% and permeability of 88 to 744 mD (horizontal permeability from analysis of offset core data). This interval is highly productive due to the clean quartzitic sandstone and preservation of high porosity and permeability.

The best reservoir quality is found in plugs taken from multi-storey fluvial channel sandstones (Figure 6). This is in part related to detrital clay content and grain size, with plugs taken from those facies being the cleanest and coarsest (lower very fine to upper coarse grained) of those cored (Figure 7a and 7b). Quartz arenites and sublithic arenites reach higher porosity and permeability values than lithic arenites, feldspathic arenites and sublithic and lithic wackes. Current burial depth, grain sorting and sandstone age do not correlate with permeability.

Reservoir quality in those tight reservoirs is very variable, locally showing permeability variation of orders of magnitude over small areas of the reservoir (dm-scale, within the same facies association). In most samples compactional porosity loss is higher than cementational porosity loss, due to a rapid and deep burial during the Carboniferous times (Figure 8). Early diagenesis exerts a large influence on present day reservoir quality and it is different in the marine facies associations and continental facies. Primary porosity within the marine facies (shoreface, delta front) is commonly occluded by detrital clay and early diagenetic dolomite and siderite. In some samples, early carbonate formation precedes mechanical compaction, stabilising the grain framework but at the same time also pervasively occluding porosity rendering the reservoir largely ineffective. Reservoir quality is better preserved in the continental facies (fluvial channels and delta plain), which were not subject to early marine diagenesis, however it is highly variable, ranging from 0.01 to 744 mD, mainly owing to later diagenetic processes. After an early period of compaction and cementation, the sandstones experienced a phase of unstable grain dissolution (probably feldspars) and likely also some carbonate dissolution, temporarily increasing reservoir quality. Another phase of deep burial and associated temperature and pressure increase resulted in fracturing, pressure dissolution and precipitation of abundant quartz overgrowths and kaolinite. Quartz overgrowths comprise two generations. Minor illite formed during the later stages of diagenesis during or after quartz formation. A late phase of ferroan dolomite appears to be the latest stage of diagenesis in most samples. Minor amounts of barite and anhydrite are locally observed occluding late dolomite. Late diagenetic dolomite and illite, despite being volumetrically minor, reduce reservoir quality in the already tightly cemented sandstones. Other authigenic phases, such as pyrite and feldspar overgrowths have very little effect on reservoir quality.

Modal porosity values from analysed thin sections from wells 43/19-1 and 42/19-2A range from 0 - 21.7% (3.4% average), with secondary pores being the dominant type (2.6% average) and primary pores subordinate (0.8%). Secondary pores, which might have led to an improved reservoir quality, probably result from feldspar dissolution.

The Westphalian A pay zone in well 43/19-1 (Crawshaw Sandstone) located just a few feet below the BPU shows anomalously high permeability values, which might be a result of leaching during the Variscan uplift. This is consistent with the model of reservoir quality enhancement by weathering beneath the exposed Variscan unconformity surface, observed by e.g. Bailey et al. (1993) and Besly et al. (1993). High permeability streaks were also recorded in 43/19-2A Westphalian A and nearby well 43/20b-2 in Namurian B strata, both of which are fractured.

Production history and reserves

The gas-initially-in-place (GIIP) determined at the time of FDP submission had a stochastic range (P90 to P10) of 166 to 403 Bscf and a P50 volume of 311 Bscf. The expected recovery (P90 to P10) was 85 to 181 Bscf with a P50 of 117 Bscf. The main volumetric uncertainty affecting GIIP was the net reservoir cut-off and effective GWC.

First gas was produced on 3rd July 2007. Well 43/19a-C1 was brought on-line with an initial rate of 61 MMscf/d. Well 43/19a-C3 came on line 9th November 2007 with similar rates and increased to 70 MMscf/d after a couple of months. Three years elapsed before 43/19a-C2Y was brought on-line 19th December 2010 with a maximum rate of 30 MMscf/d (Figure 9).

The field achieved a plateau rate of around 90 MMscf/d for a period of five months soon after 43/19a-C1 and 43/19a-C3 were both on-stream. Rates then declined until 22nd April 2009 when compression was provided through the Caister-Murdoch System facilities and this allowed production rates to be increased over a six month period. A further step-up in production occurred after work-overs on 43/19a-C1 and 43/19a-C3 followed by 43/19a-C2Y on stream in 2010. A maximum field rate of 68 MMscf/d was achieved with all three wells on-line. All the wells have exhibited steady decline although 43/19a-C2Y has declined more rapidly in comparison to 43/19a-C1 and 43/19a-C3.

The modelling and understanding of the field at the development planning stage was approached stochastically. A static model build to reflect the various fluvio-deltaic channel facies were modelled using a probabilistic approach with reference to documented examples of UK onshore Carboniferous sand body geometries. Input parameters for channel thickness, width to thickness ratios, sinuosity, amplitude and net:gross range were applied for the different stratigraphic intervals. Early simulation models developed using this approach did not reflect subsequent production behaviour, which demonstrated good connectivity within the Guiseley Grit and Crawshaw Sandstone whilst the Loxley and Alton Sandstones, when eventually developed, proved to have a very low connected volume. Rebuilding of the static model with the Crawshaw Sandstone and Guiseley Grit represented as ‘sheet’ form geometries provided an improvement but did not completely balance the connected gas volume in the Crawshaw Sandstone. Remapping was required to reduce the level of truncation at the BPU horizon and restore volume to the Crawshaw Sandstone reservoir interval. The final revised GIIP for all the developed reservoir intervals was determined as 184 Bscf.

At cessation of production in 2018 the field had produced a total volume of 98 Bscf plus associated condensate. The condensate–gas ratio was between 3.5 and 11.0 stb/MMscf (Kersten et al., 2013) and this ratio is used to calculate condensate yield which is not measured independently. Various well tests, pressure data and production logging results were used to determine the produced gas volumes by the various discreet reservoir intervals. The Crawshaw Sandstone near the base of the Westphalian A produced approximately 83 Bscf and demonstrated a recovery factor of 80% based on revised GIIP for the developed horizon. The Guiseley Grit produced 11 Bscf and recovered 39% of the GIIP volume. The younger, but of marginal reservoir quality, Loxley and Alton Sandstones produced a combined total of 4 Bscf with recovery factors of 12% and 2% respectively.

Production from Cavendish remained economic at very low levels (5 MMscf/d) achieved through the low operating costs of a minimum facilities, normally unmanned platform. Cessation of production came when the Conoco-Phillips operated Caister-Murdoch export route to LOGGS and the onshore plant at Theddlethorpe as a whole became uneconomic due to low aggregated throughput.

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FIGURES

TABLES

Table 1. *Cavendish Gas Field data summary*

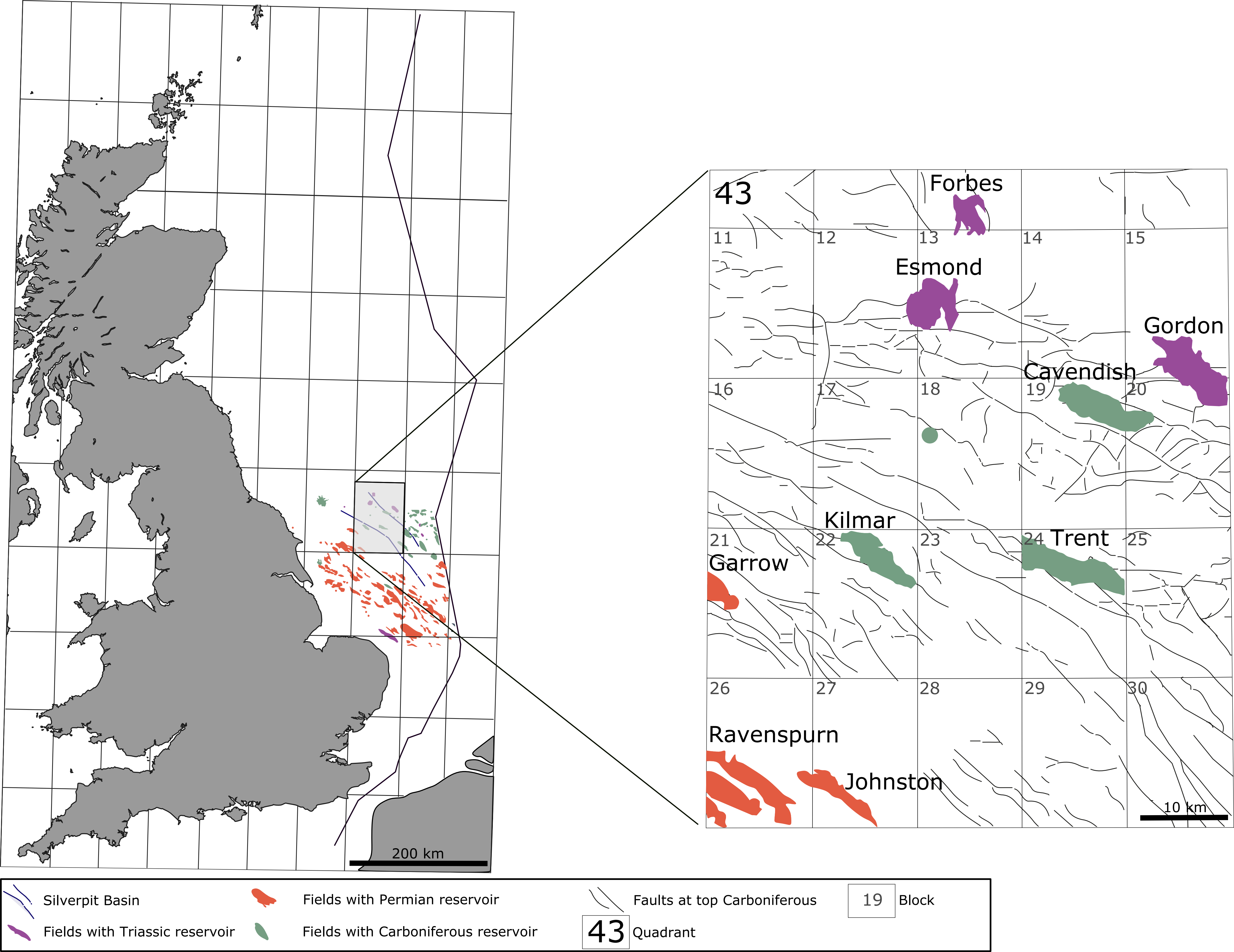
(Parameter)	*(Data and suggested Units)*	*(Author's explanatory comments)*
Trap		
Type	Dip and fault closed anticline	
Depth to crest	11550 ft SS	
Hydrocarbon contacts	11910 - 12000 ft SS	
Maximum oil column thickness	n/a ft	
Maximum gas column thickness	450 ft	
Main Pay Zone		
Formation	Caister Coal Formation, Millstone Grit Formation	
Age	Westphalian A, Namurian B - C	
Depositional setting	Deep basin progressively infilled with fluviodeltaic deposits. Reservoir in fluvial deposits.	
Gross/net thickness	1475/254 ft (43/19-1) 745/166 ft (43/19-2A)	
Average porosity (range)	7.9% (0.4-19.1%)	
Average net:gross ratio	0.17 & 0.22 (19-1&19-2A)	
Cutoff for net reservoir	7 and 8% (43/19-1 & 43/19-2A respectively); 0.1 mD	
Average permeability (range)	7.72 mD (arithmetic mean)/ 0.4 mD (geomean), range 0.01 – 744 mD	*Horizontal permeability*
Average hydrocarbon saturation	87.9 % (43/19-1)	
Productivity index range	not available	
Hydrocarbons		
Oil gravity	48.1-48.2 °API (43/19-1)	*Variation in API gravity*
Oil properties		*E.g. sulphur (%), wax (%), viscosity (cP), biodegradation, H_2S, etc.*
Bubble point (oil) Dew point (condensate)	4800-6450 psig	
Gas/Oil Ratio or Condensate/Gas Ratio	3.5 – 11 stb/MMcf	
Formation Volume	n/a	

Factor (oil)		
Gas gravity	48.1-48.2 °API condenstate	
Gas Expansion Factor	280 scf/rcf	
Formation Water		
Salinity	250000 ppm NaCl equiv. (+30000$CaCl_2$) (43/19-1)	*Identify data source – measured or computed*
Resistivity	0.0415 ohm-m at 60°F at 77°F (43/19-1)	
Pressure gradient - water	(psi/ft) 0.5psi/ft at 12200 (43/19-1)	
Reservoir Conditions		
Temperature	99°C at 11491 md brt	
Initial pressure	6107.92 psi at 11491 md brt	
Hydrocarbon pressure gradient - oil	Not available psi/ft	
Hydrocarbon pressure gradient - gas	Not available psi/ft	
Field Size		
Area	35.5 km^2	
Gross Rock Volume	Not available	
STOOIP	n/a	
Associated GIP		
Non-associated GIP	166-403 Bscf, most likely 311 Bscf	
Drive mechanism (primary, secondary)	Primary, pressure depletion	
Recovery to date - oil	100,500 boe condensate	
Recovery to date - gas	98 Bscf	
Expected ultimate recovery factor/volume - oil	n/a	
Expected ultimate recovery factor/volume - gas	53 % / 98 Bscf	
Production		
Start-up date	2007	
Number of Exploration/Appraisal Wells	5 including 2 sidetracks	
Number of Production Wells	5	
Number of Injection Wells	0	

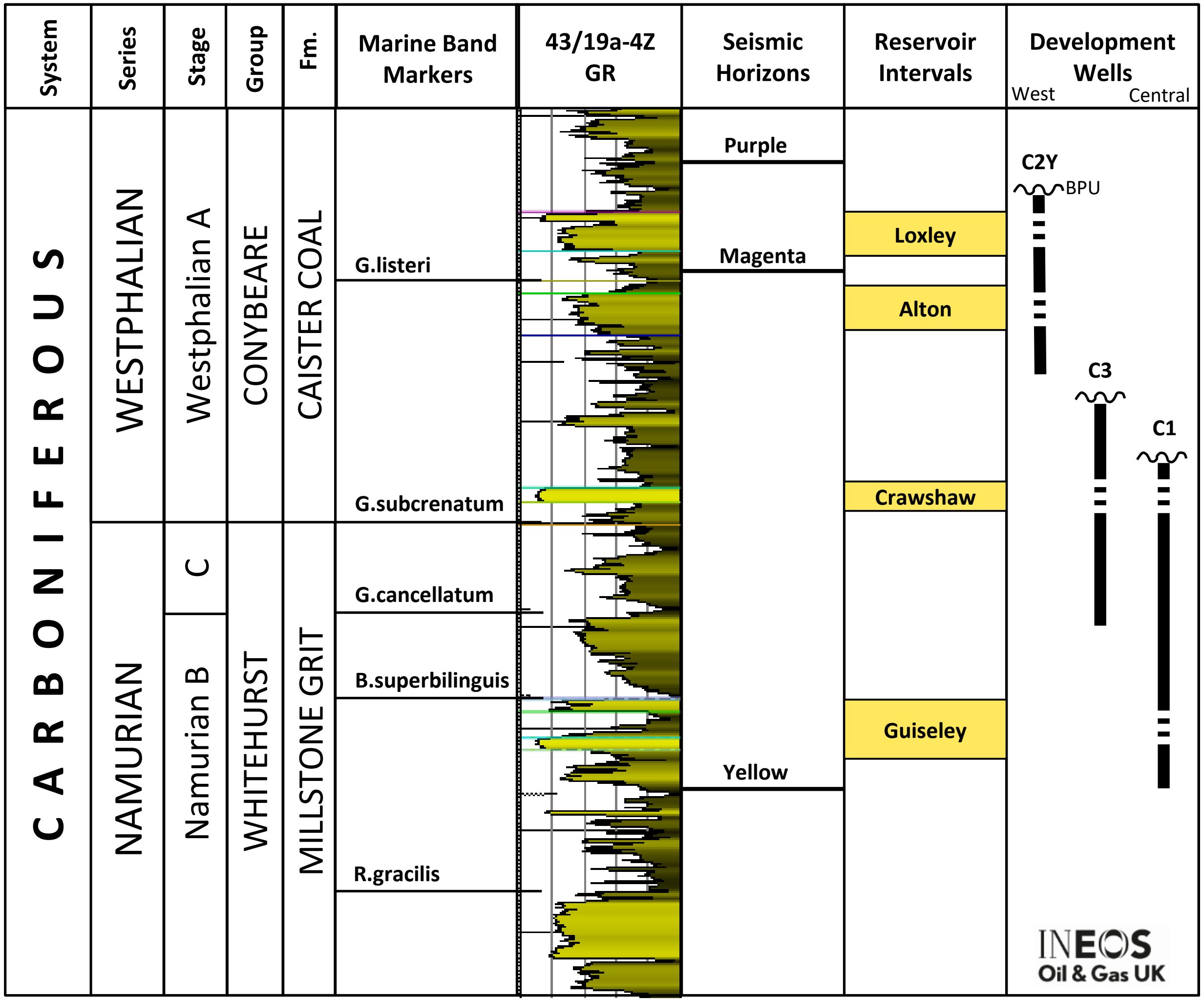
Development scheme	Gas expansion drive	
Plateau rates – oil/gas	(bopd/mmcfgd)	
Planned abandonment	2018	

Table 2. *Gas composition data for the Cavendish Field.*

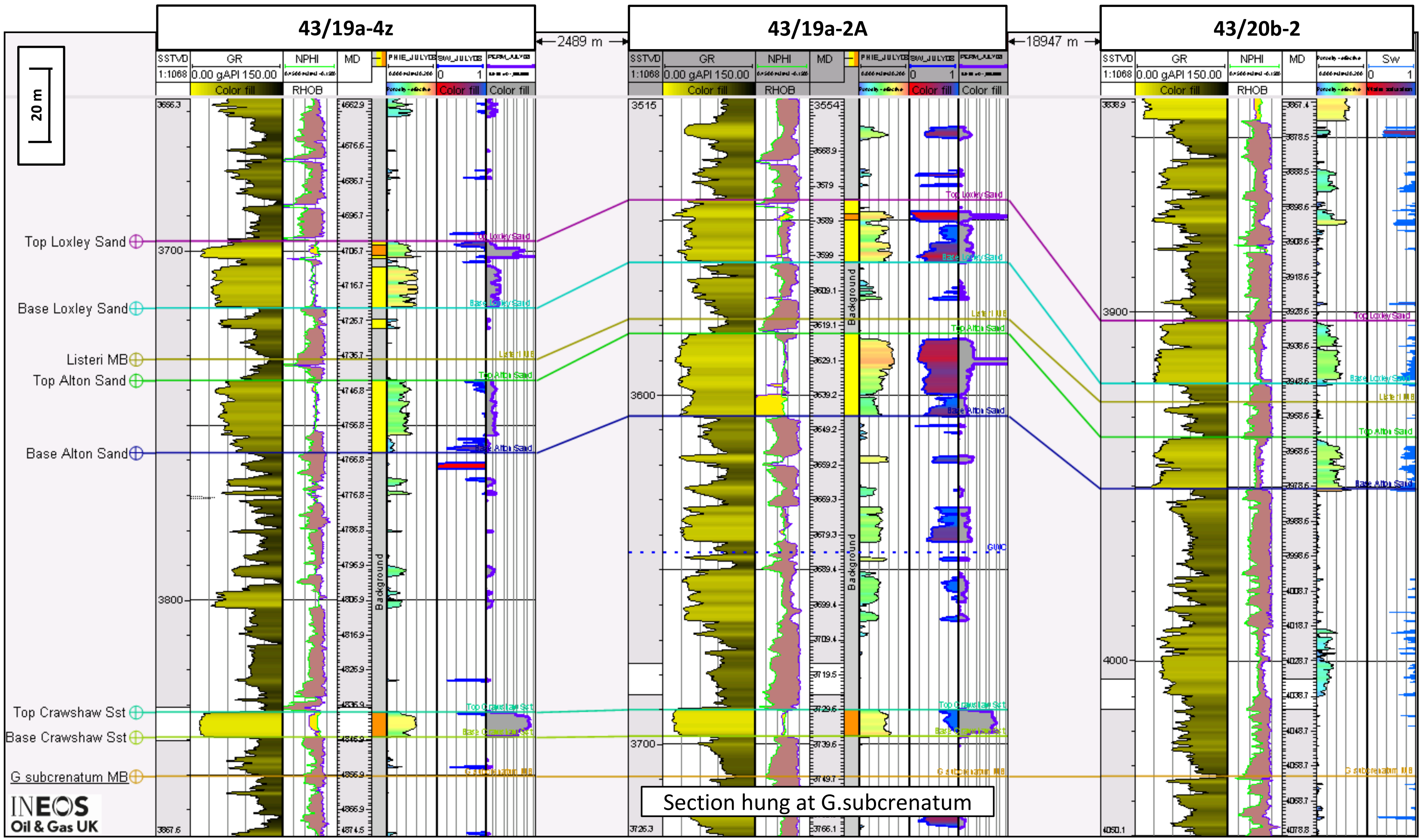
	Reservoir interval	**N_2 (%mol)**	**CO_2 (%mol)**	**C1 (%mol)**
43/19a-C1	Crawshaw and Guiseley	3.792	3.774	85.708
43/19a-C2Y	Loxley and Alton	4.399	1.502	88.163
43/19a-C3	Crawshaw	3.852	3.296	86.842



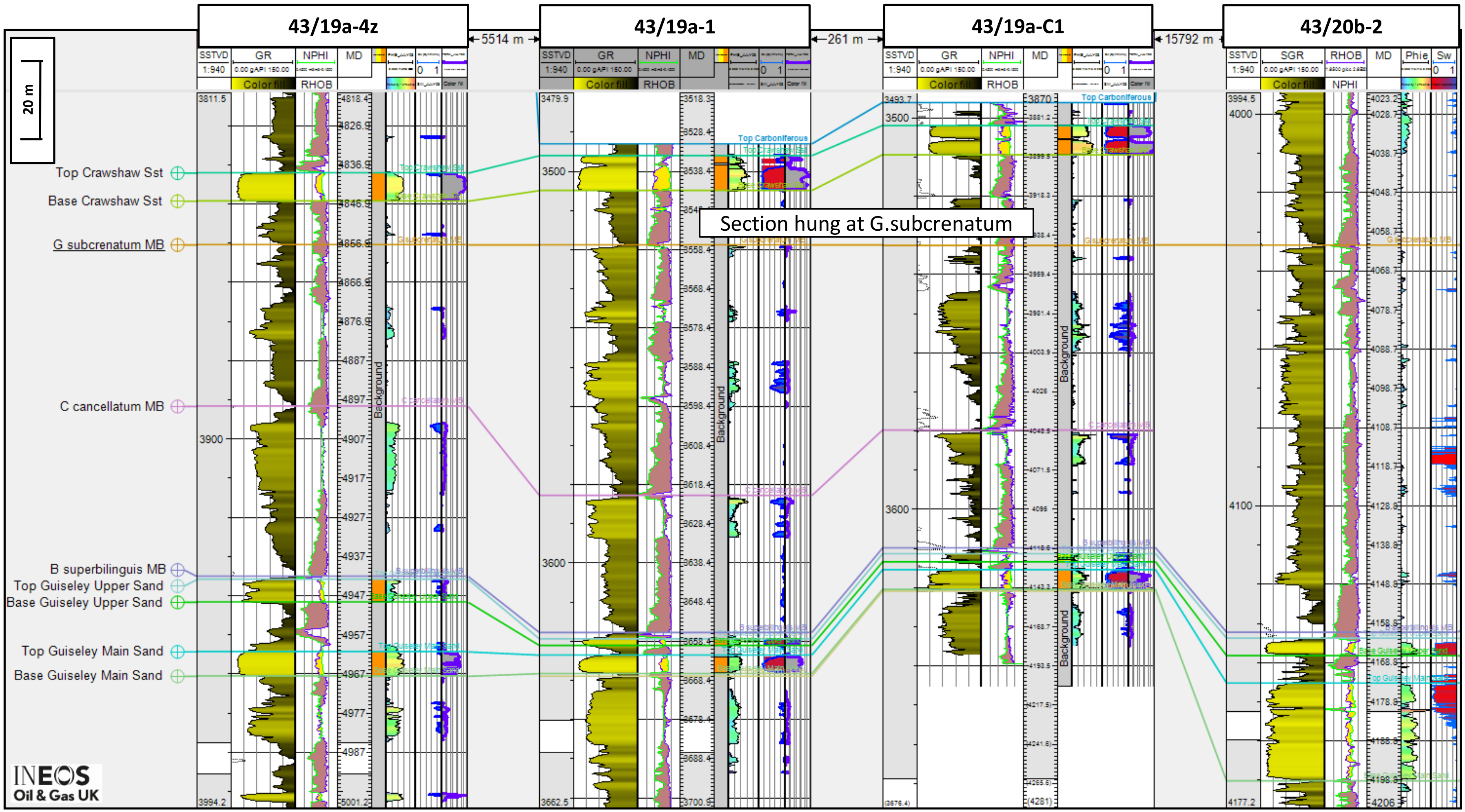
200 km
43
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Forbes
Esmond
Gordon
Cavendish
Kilmar
Trent
Garrow
Ravenspurn
Johnston
10 km
Silverpit Basin
Fields with Triassic reservoir
Fields with Permian reservoir
Fields with Carboniferous reservoir
Faults at top Carboniferous
43 Quadrant
19 Block

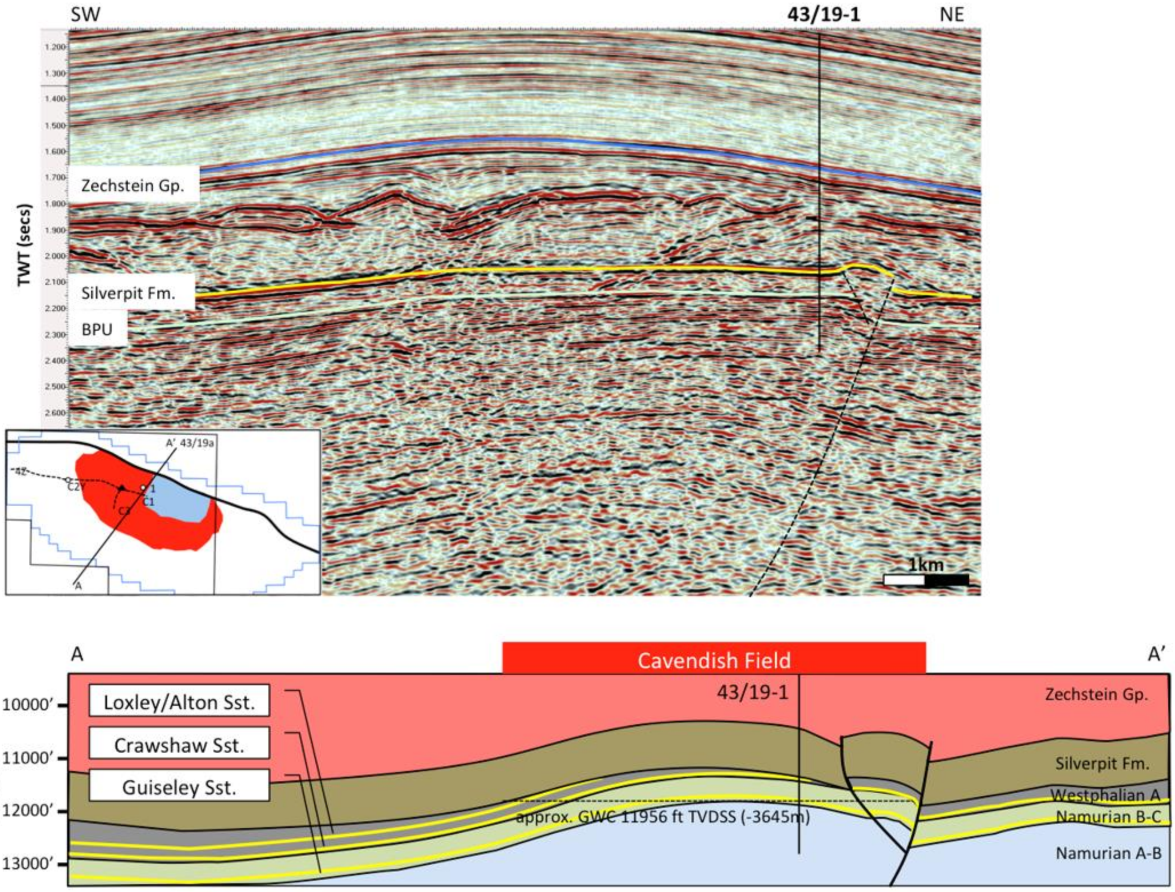

System
Series
Stage
Group
Fm.
Marine Band Markers
43/19a-4Z GR
Seismic Horizons
Reservoir Intervals
Development Wells
West
Central
CARBONIFEROUS
WESTPHALIAN
NAMURIAN
Westphalian A
C
Namurian B
CONYBEARE
WHITEHURST
CAISTER COAL
MILLSTONE GRIT
G.listeri
G.subcrenatum
G.cancellatum
B.superbilinguis
R.gracilis
Purple
Magenta
Yellow
Loxley
Alton
Crawshaw
Guiseley
C2Y
BPU
C3
C1
INEOS
Oil & Gas UK

Cavendish field

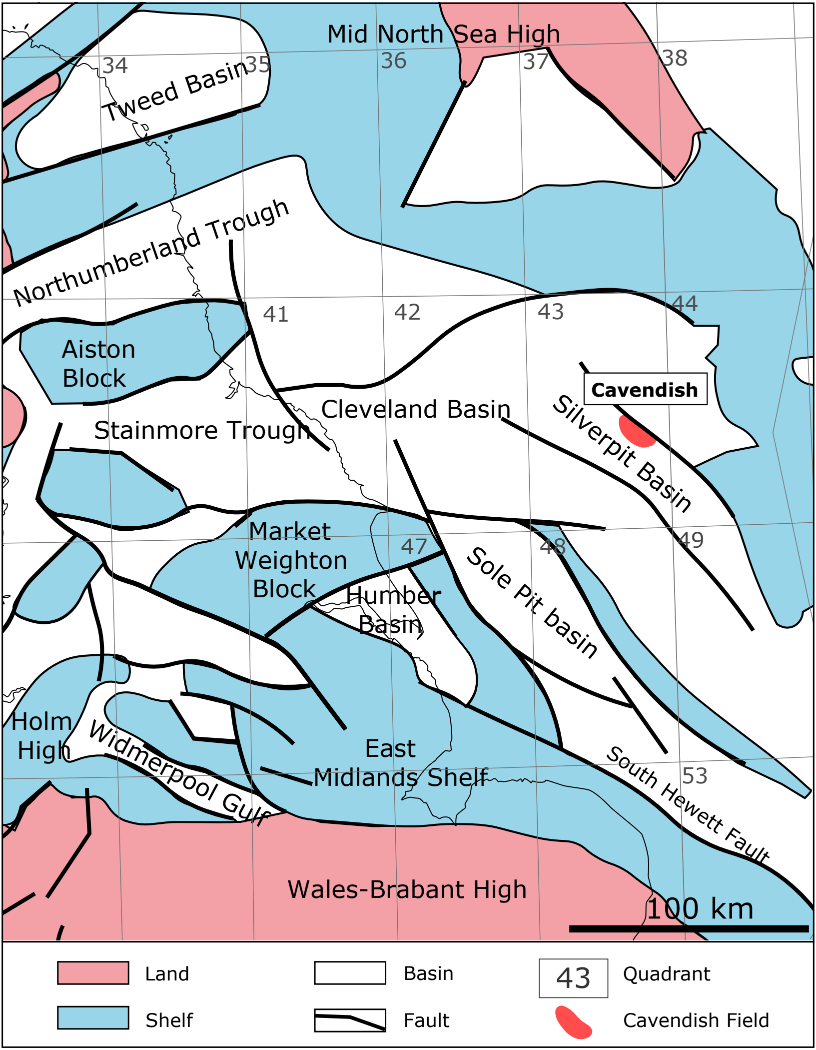


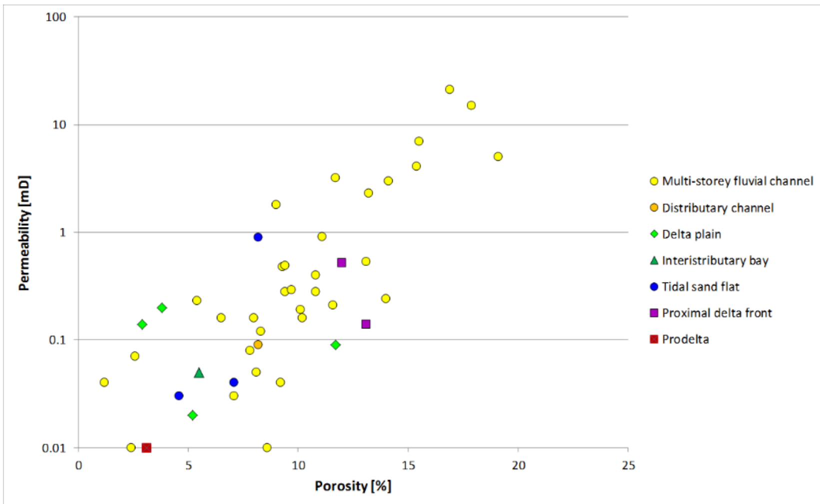
Cavendish field



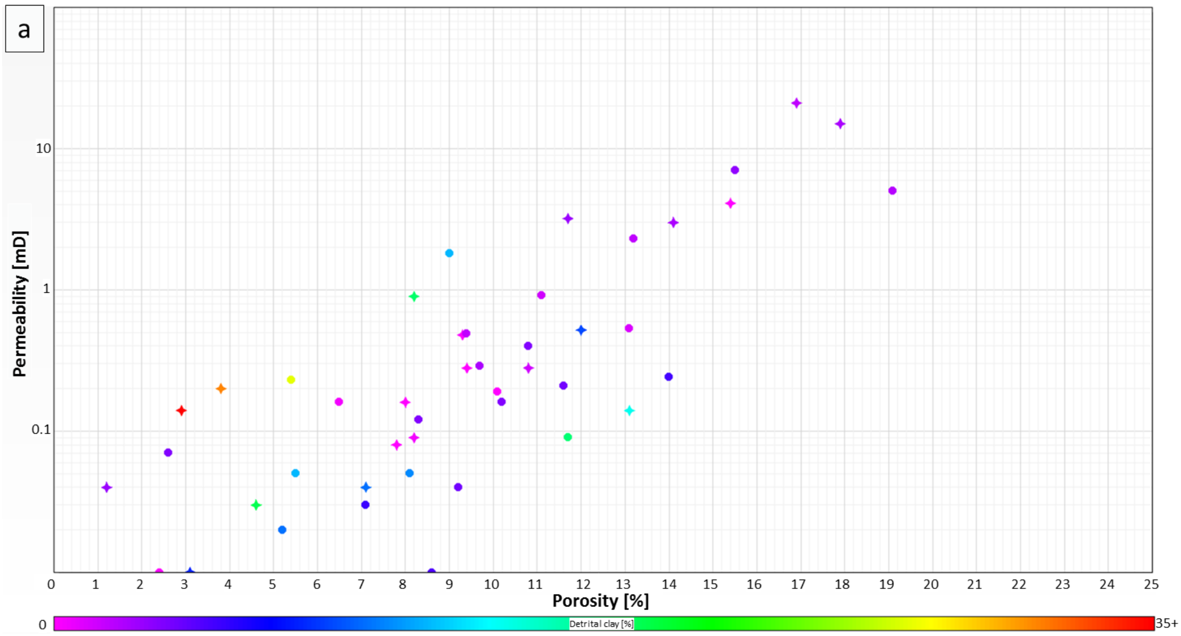


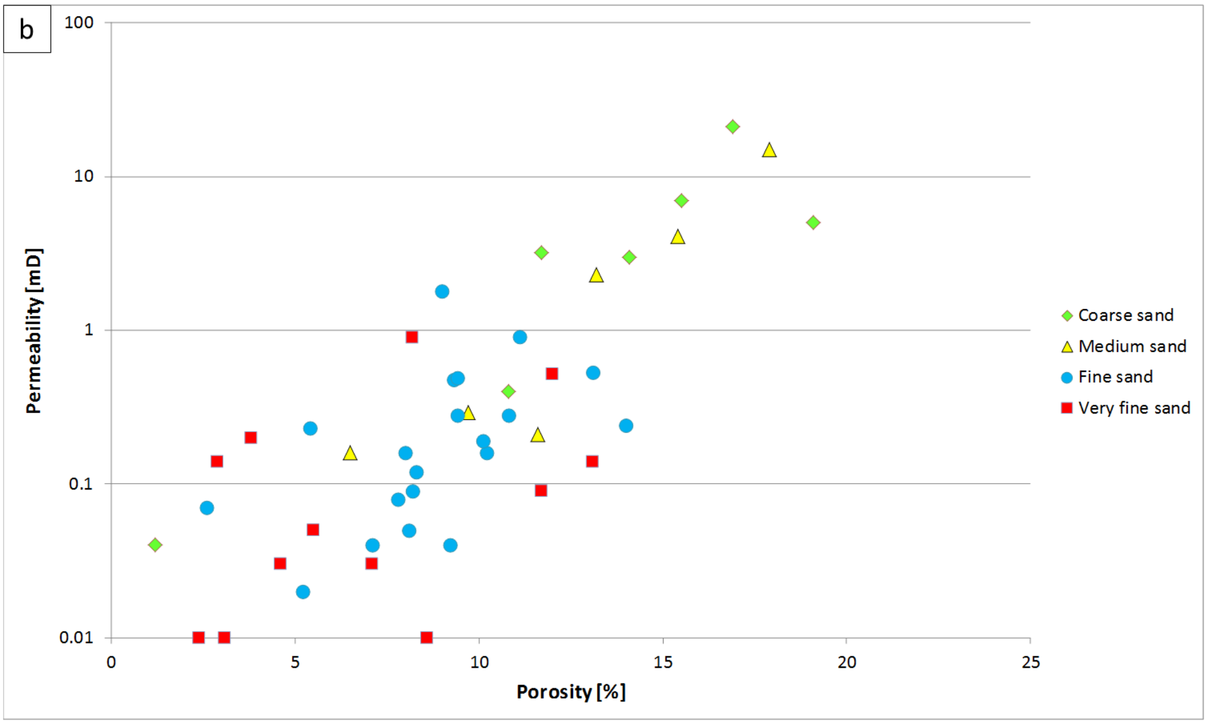
SW
43/19-1
NE
TWT (secs)
Zechstein Gp.
Silverpit Fm.
BPU
1km
A' 43/19a
A
A
Cavendish Field
A'
10000'
11000'
12000'
13000'
Ft TVDSS'
Loxley/Alton Sst.
Crawshaw Sst.
Guiseley Sst.
43/19-1
Zechstein Gp.
Silverpit Fm.
Westphalian A
Namurian B-C
Namurian A-B
approx. GWC 11956 ft TVDSS (-3645m)


Mid North Sea High
34
35
36
37
38
Tweed Basin
Northumberland Trough
41
42
43
44
Aiston Block
Cavendish
Cleveland Basin
Silverpit Basin
Stainmore Trough
Market Weighton Block
47
48
49
Humber Basin
Sole Pit basin
Holm High
Widmerpool Gulf
East Midlands Shelf
South Hewett Fault
53
Wales-Brabant High
100 km
Land
Shelf
Basin
Fault
43
Quadrant
Cavendish Field

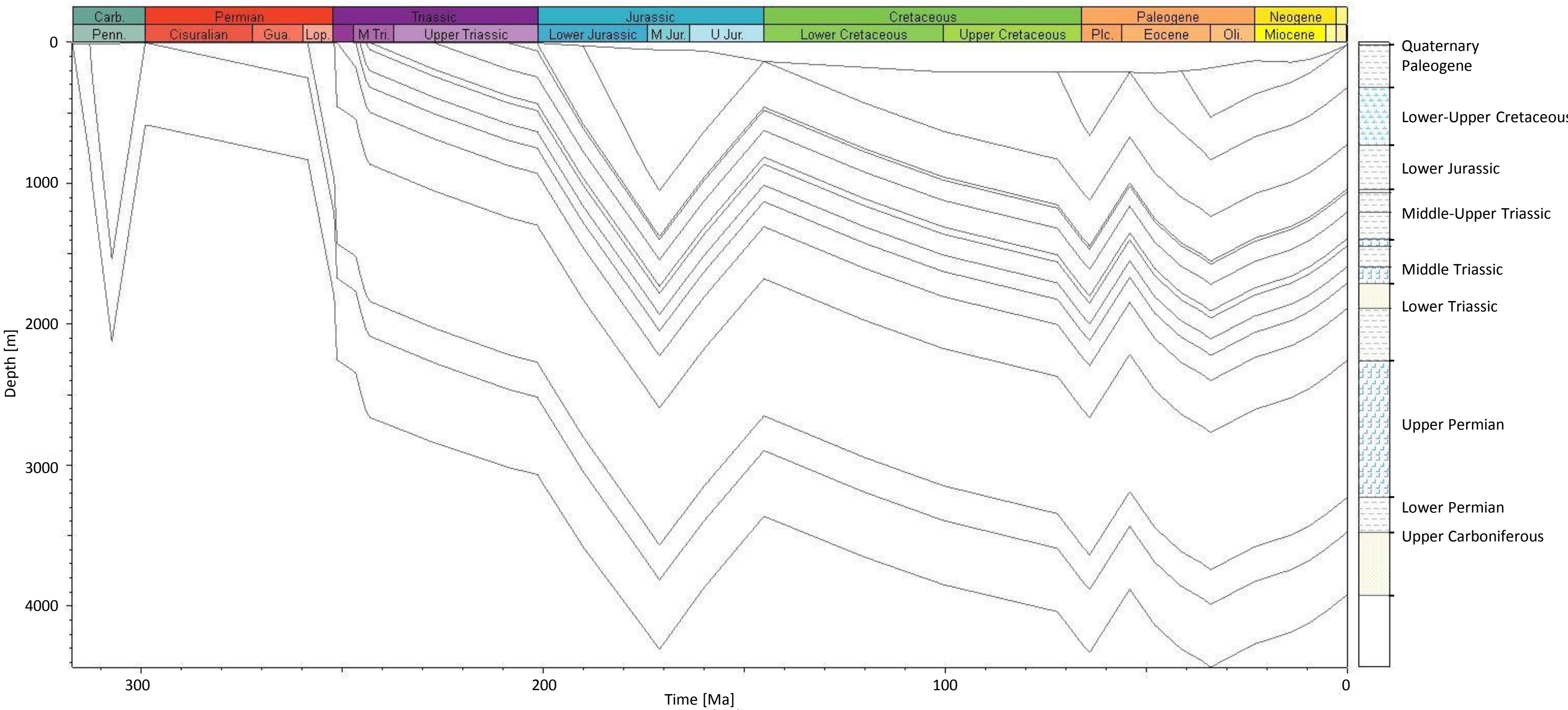


100
10
1
0.1
0.01
Permeability [mD]
0
5
10
15
20
25
Porosity [%]
Multi-storey fluvial channel
Distributary channel
Delta plain
Interistributary bay
Tidal sand flat
Proximal delta front
Prodelta

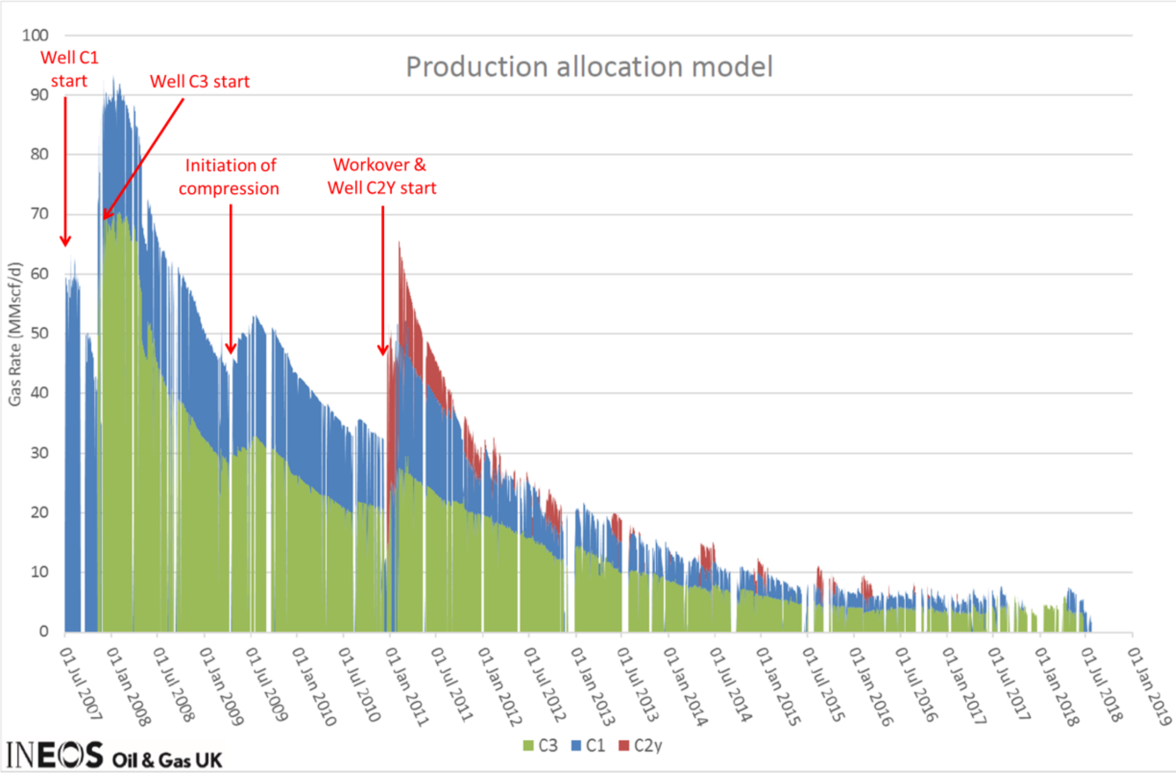

a
Permeability [mD]
10
1
0.1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Porosity [%]
0
Detrital clay [%]
35+



b
100
10
1
0.1
0.01
0
5
10
15
20
25
Permeability [mD]
Porosity [%]
Coarse sand
Medium sand
Fine sand
Very fine sand



Carb.
Permian
Triassic
Jurassic
Cretaceous
Paleogene
Neogene
Penn.
Cisuralian
Gua.
Lop.
M Tri.
Upper Triassic
Lower Jurassic
M Jur.
U Jur.
Lower Cretaceous
Upper Cretaceous
Plc.
Eocene
Oli.
Miocene
Depth [m]
0
1000
2000
3000
4000
Time [Ma]
300
200
100
0
Quaternary
Paleogene
Lower-Upper Cretaceous
Lower Jurassic
Middle-Upper Triassic
Middle Triassic
Lower Triassic
Upper Permian
Lower Permian
Upper Carboniferous


Production allocation model
Gas Rate (MMscf/d)
100
90
80
70
60
50
40
30
20
10
0
Well C1 start
Well C3 start
Initiation of compression
Workover & Well C2Y start
01 Jul 2007
01 Jan 2008
01 Jul 2008
01 Jan 2009
01 Jul 2009
01 Jan 2010
01 Jul 2010
01 Jan 2011
01 Jul 2011
01 Jan 2012
01 Jul 2012
01 Jan 2013
01 Jul 2013
01 Jan 2014
01 Jul 2014
01 Jan 2015
01 Jul 2015
01 Jan 2016
01 Jul 2016
01 Jan 2017
01 Jul 2017
01 Jan 2018
01 Jul 2018
01 Jan 2019
C3
C1
C2y
INEOS Oil & Gas UK